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Evaluation of Gafchromic EBT2 film for the measurement of anisotropy function for high-dose-rate ^{192}Ir brachytherapy source with respect to thermoluminescent dosimetry

Satish C. Uniyal[a,*], *Umesh C. Naithani*[b], *Sunil D. Sharma*[c]

[a] *Department of Radiology, Himalayan Institute of Medical Sciences, Jolly Grant, Dehradun 248140, India*
[b] *Department of Physics, H N B Garhwal Central University, Campus Pauri, Pauri (Garhwal), Uttarakhand 246001, India*
[c] *Radiological Physics & Advisory Division, Bhabha Atomic Research Centre, CT & CRS Building, Anushaktinagar, Mumbai 400094, India*

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ABSTRACT

Aim: The aim of this work was to assess the suitability of the use of a Gafchromic EBT2 film for the measurement of anisotropy function for microSelectron HDR ^{192}Ir (classic) source with a comparative dosimetry method using a Gafchromic EBT2 film and thermoluminescence dosimeters (TLDs).
Background: Sealed linear radiation sources are commonly used for high dose rate (HDR) brachytherapy treatments. Due to self-absorption and oblique filtration of radiation in the source capsule material, an inherent anisotropy is present in the dose distribution around the source which can be described by a measurable two-dimensional anisotropy function, $F(r, \theta)$.
Materials and methods: Measurements were carried out in a specially designed and locally fabricated PMMA phantom with provisions to accommodate miniature LiF TLD rods and EBT2 film dosimeters at identical radial distances with respect to the ^{192}Ir source.
Results: The data of anisotropy function generated by the use of the Gafchromic EBT2 film method are in agreement with their TLD measured values within 4%. The produced data are also consistent with their experimental and Monte Carlo calculated results for this source available in the literature.
Conclusion: Gafchromic EBT2 film was found to be a feasible dosimeter in determining anisotropy in the dose distribution of ^{192}Ir source. It offers high resolution and is a viable alternative to TLD dosimetry at discrete points. The method described in this paper is useful for comparing the performances of detectors and can be applied for other brachytherapy sources as well.

1. Background

High dose rate ^{192}Ir sources are commonly used in brachytherapy by most of the radiotherapy centers. Ideally, a treatment source would be a point source, but in reality the geometry is

* *Corresponding author.*
E-mail address: uniyal.satish@rediffmail.com (S.C. Uniyal).

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more complex. In remote afterloading High Dose Rate (HDR) brachytherapy the ^{192}Ir source is normally cylindrical, made of high-Z elements and encapsulated in stainless steel. Due to self-absorption and oblique filtration of radiation in the capsule material, the dose distribution is inherently anisotropic around the HDR ^{192}Ir source. According to the dose calculation model as recommended by American Association of Physicists in Medicine (AAPM), Task Group No. 43 reports TG-43U1,[1,2] a two-dimensional angular anisotropy function, $F(r, \theta)$ accounts for anisotropic dose distribution around brachytherapy sources.

Previous studies using different detectors such as TLDs, radiochromic film, diodes and ionization chambers have measured anisotropy function for HDR ^{192}Ir source at various radial distances through a range of polar angles.[3–12] Most of them have used either a single detector or different detectors in separate experimental settings for dosimetric characterization of the source. Employing different detectors in a single experimental set up may provide a faithful comparison between performances of detectors. A reliable comparative dosimetry data is of significant importance for the purpose of clinical quality control.

Lithium fluoride (LiF) thermoluminescence dosimetry (TLD) is the recommended method for experimental determination of dose around brachytherapy sources because it offers best compromise between relatively small size, flat energy response and high sensitivity. However, it has many associated artifacts such as volume averaging, inter-detector and self attenuation, positioning errors at short distances and higher total uncertainty in dose determination. The recently introduced Gafchromic EBT2 film has been mainly targeted towards application in external beam radiotherapy and found less application in brachytherapy dosimetry. However, due to its high resolution and other favorable properties, the EBT2 film promises to be a suitable detector for point dose measurement in brachytherapy.

2. Aim

The present work was aimed to evaluate the feasibility of radiochromic film dosimetry using Gafchromic EBT2 model in determining the anisotropy function for microSelectron ^{192}Ir HDR source with respect to the validated method of thermoluminescence dosimetry. It was also intended to device a dosimetry technique to use both detectors simultaneously in identical conditions of phantom material and their spatial geometry with respect to the source for a reliable comparison.

3. Materials and methods

3.1. *microSelectron HDR ^{192}Ir source and dosimeters*

Measurement of the anisotropy function was carried out for microSelectron HDR ^{192}Ir source (classic/old source) which has an active length of 3.5 mm and active diameter of 0.6 mm. It is encapsulated in a cylindrical stainless steel capsule with an outer diameter of 1.1 mm and length of 5.0 mm. It is not completely symmetrical with respect to its transverse axis and has one end welded to a stainless steel drive cable, which is connected to stepping motors that can precisely position the source into the required applicator.[13]

Thermoluminescent dosimeters [LiF:Mg, Ti (TLD-100)] in the form of cylindrical rods with a length of 6 mm and diameter of 1 mm were used for the measurement of anisotropy in the dose distribution around the source. The TLD rods were stored in aluminum trays and were numbered to their corresponding position in the phantom for identification purpose in the course of annealing and reading. A batch of 70 fresh TLD rods was used in this measurement. Before each exposure, TLD rods were annealed in groups using a thermal cycle: 400 °C for 1 h, fast cooling for 6 min followed by 100 °C for 2 h. For the readout of TLD rods, a TLD reader model UL-320 (Rexon) was used with a purified N_2 atmosphere. Readings were taken after 24 h of irradiation. The dose response of TLD rods was obtained by exposing them to a ^{60}Co gamma rays beam (Bhabhatron-II, BARC, Mumbai/PMT, Bangalore, India). From TL (thermoluminescent) outputs, the individual calibration factors for TLD rods were determined in terms of nC/cGy to be used to evaluate absorbed doses from their TL outputs in subsequent measurements.

The Gafchromic EBT2 dosimetry film (ISP Technologies, Lot Number F020609) used in our work is a recently introduced high spatial resolution and high sensitive dosimetry film which can be used in the dose range 0.01–40 Gy. The active part of the film is a single sensitive layer about 30 μm in thickness with a thin topcoat made on a clear 175 μm thick polyester substrate. Coated to the active layer is polyester over-laminate (50 μm thick) with a pressure-sensitive adhesive layer with thickness of 25 μm. The film is near tissue equivalent with $Z_{eff} = 6.84$, which is also very close to the effective atomic number of PMMA ($Z_{eff} = 6.5$). In comparison to earlier radiochromic film models, EBT2 film shows less energy dependency. In addition, it develops in real time with density changes stabilizing rapidly after exposure. For calibration, EBT2 film samples of size 3 cm × 3 cm were placed in a full scatter PMMA phantom and irradiated in a ^{60}Co γ-ray beam (Bhabhatron-II, BARC, Mumbai/PMT, Bangalore) in the dose range 25–800 cGy. One such sample was left unexposed but kept with other samples for background optical density. After 24 h of irradiation, each sample was scanned in landscape orientation and in a red color channel mode of a flatbed scanner Epson Expression 10000 XL. The optical density (OD) of each pixel in the central 1 cm × 1 cm region of the calibration film was measured from the corresponding scan value and the film background scan value. Mean optical density (MOD) for each calibration film was then calculated. A curve between MOD and corresponding dose for the EBT2 film was plotted (Fig. 1) and a fit equation (Eq. (1)) was obtained for determination of the dose from the measured optical density in the subsequent experiment.

$$y = 1897x^2 + 696.3x \quad (1)$$

where x is the optical density and y is the dose in cGy.

3.2. *Experimental technique*

A precisely machined polymethyl methacrylate PMMA phantom was used for the measurement of anisotropy function for

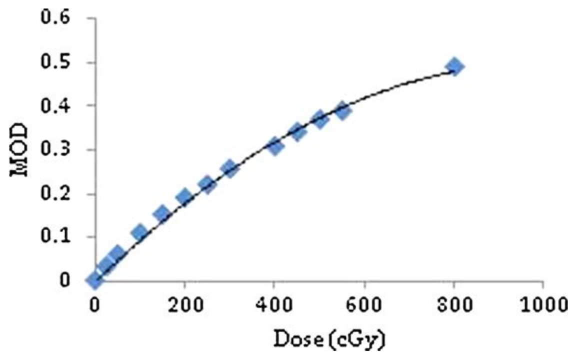

Fig. 1 – Calibration curve of Gafchromic EBT2 film at Co-60 γ-ray quality.

the source. PMMA has remained a phantom material of choice used in brachytherapy dosimetry by many researchers due to its low effective atomic number ($Z_{eff} = 6.5$), ease of machining, low cost and better availability. The phantom contains a central PMMA slab with dimensions of 25 cm × 25 cm × 0.7 cm which has a circular groove where a precisely structured PMMA disc with diameter of 22 cm can be positioned. A groove with an inner diameter of 2 mm was machined radially into the circular slab at the centre of its thickness to position a plastic bronchial applicator. The ^{192}Ir source was positioned inside the applicator to ascertain the position of the source centre at the geometric centre of the slab. A part of the circular slab has a pattern of precisely machined holes 1.5 mm in diameter and 7 mm deep to position TLD rods at radial distances from 1.0 to 10.0 cm in increments of 1.0 cm and at angles 30°, 45°, 60°, 90°, 120°, 135° and 150°. TLD rods must be perpendicular to the plane of the central slab and their centres lying in the plane of the source centre. Another part of the PMMA slab is precisely machined into 'C' shaped semi-circular strips with a width of 9.5 mm arced from 0° to 195° to accommodate EBT2 films between each pair of semi-circular strips. Films cut in required dimensions can be placed in radii (r) of 1.0–10.0 cm in increments of 1.0 cm from the source with their surfaces normal to the phantom plane and facing the source. The edges and surfaces of the strips were smoothened so that they did not cause scratches on the films. Measurements were carried out by placing additional plane PMMA slabs on both sides of the central machined slab to create a 25 cm × 25 cm × 20.7 cm full scattering volume. A line diagram of the central PMMA slab of the phantom used for the measurements of anisotropy function for the ^{192}Ir HDR source is shown in Fig. 2.

Properly annealed TLD rods were batched and rectangular EBT2 film samples with a width of 0.6 mm and length $(1.083\pi r - 0.1)$ cm were prepared. Before placing TLD rods and EBT2 film samples into the phantom for measurement, the correct source position into the phantom with respect to the arrangement of detectors was verified. A square piece of the EBT2 film was placed on the central PMMA slab in such a way that its geometric centre exactly coincided with the centre of the slab. A dwell position to drive the source at the centre of the slab was planned and an exposure was made. The exposed film was digitized and intensity profiles along the longitudinal and transverse axes of the source were plotted. The maximum intensity (peak of the profile) for both axes was obtained corresponding to the geometric centre of the film, which confirmed the correct position of the source in the applicator. The

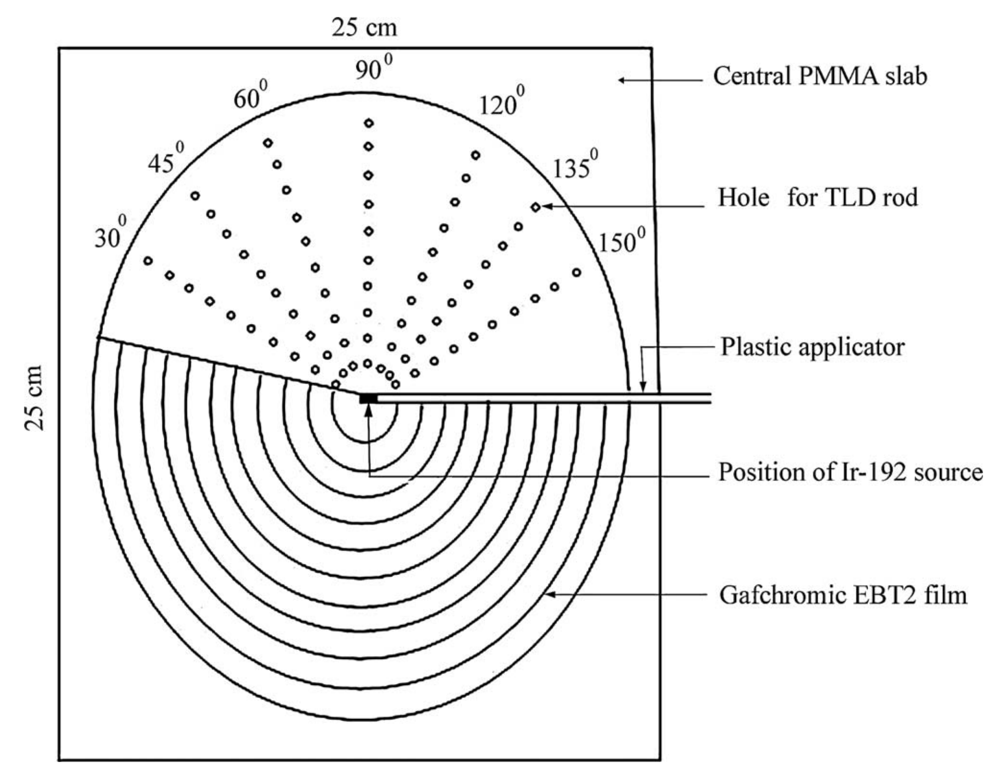

Fig. 2 – Schematic diagram showing experimental setup of TLD and Gafchromic EBT2 film dosimeters in central PMMA slab of the phantom used for the measurement of anisotropy function for microSelectron HDR Ir-192 source.

Table 1 – Anisotropy function measured with TLD at distances from 1 to 10 cm for the Ir-192 source.

Angle, θ (°)	Anisotropy function, $F(r, \theta)$									
	1 cm	2 cm	3 cm	4 cm	5 cm	6 cm	7 cm	8 cm	9 cm	10 cm
30	0.9238	0.9519	0.9477	0.9492	0.9424	0.9467	0.9583	0.9475	0.9191	0.9321
45	0.9651	1.0015	0.9884	0.9797	0.9864	0.9829	0.9802	0.9699	0.9793	0.9613
60	1.0085	1.0057	0.9914	1.0041	1.0019	1.0056	0.9988	0.9914	0.9836	0.9741
90	1	1	1	1	1	1	1	1	1	1
120	0.9898	0.9777	0.9891	0.9946	0.9872	0.9860	0.9802	0.9963	0.9813	0.9917
135	0.9603	0.9392	0.9479	0.9574	0.9624	0.9722	0.9694	0.9807	0.9462	0.9595
150	0.8930	0.8865	0.8868	0.8856	0.9292	0.9187	0.9077	0.9090	0.9260	0.9080

TLD rods were placed in the machined slab in a full scattering volume and irradiated using a dwell time to deliver doses <185 cGy. The exposed TLDs were removed and EBT2 film samples were placed in the designated positions into the phantom and similarly irradiated using a dwell time to deliver doses ≤700 cGy.

During irradiation, the care was taken to maintain the radiation dose to the TLDs within the linear range of their response. The dose rate to water at polar coordinates (r, θ) per unit air kerma strength (S_k) with respect to the source was calculated using the equation[14,15]:

$$\frac{\dot{D}(r,\theta)}{S_k} = \frac{kR_{i,(r,\theta)}F_l}{S_k \mathrm{CF}_i T\, \mathrm{d}t\, E_r} \tag{2}$$

where k is a dose conversion factor from PMMA to water; $R_{i,(r,\theta)}$ is the TL output (nC) corrected for background of irradiated ith TLD rod placed at (r, θ); F_l is the correction to account for the finite length of TLD rods which is equal to the ratio of dose at geometric centre of the detector to that averaged over the length of the detector. In this work, we used the published value of this correction factor (1.03 at 1.0 cm and 1.0 beyond 1.0 cm) which is derived from geometrical considerations[15]; CF_i is the calibration factor for the ith TLD rod (nC/cGy) measured at ^{60}Co gamma ray energy; T is the time of irradiation (s); dt is the correction factor used to account for the decay of the ^{192}Ir source during irradiation (considered unity as the time of irradiation was negligibly small in comparison to the half-life of ^{192}Ir); and E_r is the correction factor for the energy dependence of the TLD response between ^{60}Co beam and ^{192}Ir source. In this work, we used the published numerical value of 1.001 of Pradhan.[16] The TLD data at each point in the phantom were taken from the average of three measurements with a combined experimental uncertainty of about 7%.

The exposed Gafchromic EBT2 film samples were scanned in landscape orientation in a red color channel mode of Epson flatbed scanner and their images were acquired. Scan values of these images along their lengths were obtained and converted into optical density (OD) using the following relation:

$$\mathrm{OD} = \log_{10}\frac{P_b}{P_i} \tag{3}$$

where P_b is the average of the film background scan values measured from unexposed samples and P_i is the measured film scan value in the region of interest. Pixel number corresponding to every polar angle (in°) was found by correlating the film length used and the range of polar angle covered. MOD for a polar angle was then calculated by averaging the OD of three consecutive pixels, one corresponding to the polar angle and two on its both sides. The MOD for each polar angle of interest was converted into absorbed dose by using the previously obtained fit equation (Eq. (1)). Corresponding values of dose rate to water were then calculated by using the time of irradiation (s) and the dose conversion factor from PMMA to water.

From the above measured values of dose rate (in TLD and Gafchromic film measurements), the AAPM TG-43 U1[1,2] recommended anisotropy function was calculated using Eq. (4):

$$F(r,\theta)\frac{\dot{D}_{(r,\theta)}G_{(r,\pi/2)}}{\dot{D}_{(r,\pi/2)}G_{(r,\theta)}} \tag{4}$$

where $\dot{D}_{(r,\theta)}$ is the dose rate at polar coordinates (r, θ) with respect to the source centre and G(r, θ) is the associated geometry function which was analytically calculated using the following expression[17]:

$$G(r,\theta) = \frac{\tan^{-1}[L/2r\sin\theta + \cot[\theta]] + \tan^{-1}[L/2r\sin\theta - \cot[\theta]]]}{Lr\sin\theta} \tag{5}$$

where L is the active length of the source (in cm), r and θ are in cm and radian, respectively.

4. Results and discussion

The TLD measured anisotropy function at radial distances from 1 to 10 cm in increments of 1 cm is presented in Table 1. It is apparent from the values that the anisotropy function varies with the polar angle. It increases from the longitudinal axis of the source and gets stabilized at or near the transverse axis of the source. The values of F(r, θ) measured with the EBT2 film at similar radial distances as in the TLD set-up are shown in Table 2. A slight asymmetry in the data about the transverse axis of the source is seen with a forward bulge. A comparison between the produced film and TLD results shows that the results of the anisotropy function are in agreement with each other within 4% (Table 3). The deviation between the two sets of data could be due to differences in dosimetry techniques, detector's size and their sensitivities. Comparing TLD results with similar measurements by Anctil et al.[10] shows a variation up to about 3%. Results of our film measurements were compared with radiochromic film values of Sharma et al.,[12] TLD measured values of Anctil et al.,[10] and Monte Carlo calculated results of Williamson and Li,[13] for the same source. The comparison shows that from 1 cm to 5 cm, our film data deviate from those of Sharma et al.[12] and Williamson and Li,[13]

Table 2 – Anisotropy function measured with Gafchromic EBT2 film at distances from 1 to 10 cm for the Ir-192 source.

Angle, θ (°)	Anisotropy function, $F(r, \theta)$									
	1.0 cm	2.0 cm	3.0 cm	4.0 cm	5.0 cm	6.0 cm	7.0 cm	8.0 cm	9.0 cm	10.0 cm
0			0.6525	0.6815	0.7033	0.7124	0.7230	0.7409	0.7321	0.7407
5		0.6774	0.6978	0.7212	0.7403	0.7586	0.7567	0.7649	0.7716	0.7748
10	0.7468	0.7683	0.7728	0.7800	0.7912	0.7959	0.7971	0.8157	0.8119	0.8235
15	0.8011	0.8083	0.8108	0.8169	0.8410	0.8305	0.8337	0.8547	0.8465	0.8492
20	0.8527	0.8633	0.8650	0.8603	0.8882	0.8579	0.8579	0.8825	0.8679	0.8773
25	0.8801	0.9007	0.9022	0.8861	0.9019	0.8773	0.8939	0.8982	0.8929	0.8996
30	0.9177	0.9231	0.9190	0.9143	0.9211	0.9122	0.9260	0.9157	0.9136	0.9251
35	0.9338	0.9390	0.9397	0.9276	0.9285	0.9416	0.9356	0.9378	0.9391	0.9364
40	0.9377	0.9554	0.9626	0.9464	0.9685	0.9569	0.9440	0.9447	0.9501	0.9526
45	0.9478	0.9828	0.9719	0.9554	0.9718	0.9662	0.9546	0.9490	0.9593	0.9646
50	0.9560	0.9851	0.9716	0.9640	0.9729	0.9752	0.9627	0.9561	0.9784	0.9739
55	0.9765	0.9891	0.9784	0.9815	0.9755	0.9869	0.9722	0.9708	0.9791	0.9850
60	0.9835	0.9969	0.9835	0.9896	0.9849	0.9865	0.9783	0.9712	0.9839	0.9865
65	0.9934	1.0019	0.9909	0.9936	0.9895	0.9906	0.9785	0.9893	0.9970	0.9918
70	1.0032	0.9971	0.9985	1.0023	0.9959	0.9811	0.9820	0.9984	0.9948	0.9946
75	1.0063	1.0060	0.9997	0.9895	1.0002	0.9898	0.9850	0.9871	0.9956	0.9997
80	1.0105	1.0030	0.9993	1.0036	1.0087	0.9894	0.9945	0.9876	1.0067	0.9957
85	1.0043	1.0031	0.9964	0.9893	1.0031	0.9955	0.9986	0.9930	0.9957	0.9921
90	1	1	1	1	1	1	1	1	1	1
95	1.0080	1.0058	0.9937	1.0121	0.9892	0.9867	0.9942	0.9974	1.0024	0.9920
100	1.0108	1.0051	1.0029	0.9932	0.9939	0.9902	0.9972	0.9928	0.9997	0.9949
105	1.0078	0.9983	0.9898	0.9969	1.0066	0.9935	0.9999	0.9966	1.0050	0.9905
110	0.9990	1.0012	0.9881	0.9996	0.9911	0.9881	0.9970	0.9992	0.9990	0.9892
115	0.9902	1.0019	0.9841	0.9849	0.9756	0.9806	0.9863	0.9900	0.9907	0.9864
120	0.9750	0.9899	0.9797	0.9915	0.9723	0.9737	0.9764	0.9867	0.9827	0.9760
125	0.9699	0.9862	0.9779	0.9698	0.9810	0.9697	0.9753	0.9808	0.9856	0.9760
130	0.9506	0.9791	0.9665	0.9590	0.9559	0.9626	0.9705	0.9629	0.9778	0.9563
135	0.9393	0.9664	0.9411	0.9483	0.9417	0.9356	0.9571	0.9570	0.9666	0.9536
140	0.9229	0.9446	0.9248	0.9345	0.9270	0.9166	0.9359	0.9471	0.9496	0.9334
145	0.9021	0.9194	0.9123	0.8987	0.9105	0.8983	0.9090	0.9374	0.9422	0.9108
150	0.8854	0.9010	0.8898	0.8874	0.8944	0.8873	0.8892	0.9127	0.9191	0.8994
155	0.8574	0.8875	0.8633	0.8446	0.8621	0.8556	0.8725	0.8885	0.8959	0.8838
160	0.8211	0.8242	0.8363	0.8217	0.8503	0.8210	0.8634	0.8594	0.8778	0.8632
165	0.7738	0.7960	0.8061	0.7912	0.8152	0.8019	0.8196	0.8367	0.8411	0.8370
170	0.7179	0.7366	0.7482	0.7495	0.7643	0.7579	0.7809	0.8009	0.8173	0.7924
175	0.6676	0.6497	0.6678	0.6754	0.6939	0.6990	0.6853	0.7248	0.7378	0.7145

by up to 3% and 4%, respectively. The maximum discrepancy between our film result and that of TLD measured values of Anctil et al.[10] was found to be 6%. A comparison of $F(5, \theta)$ measured in the present experiment and determined by other authors is shown in Fig. 3.

Although TLD is a recommended detector for brachytherapy dosimetry, self filtration and volume averaging due to the finite size of the detector make it difficult to obtain unperturbed values of dose. Reducing the size of TLD detector poses practical limitations related to phantom construction and accurate positioning of the detector, thereby limiting measurement accuracy and inter-investigator agreement. To improve uncertainty in TLD results, repeated measurements are required. In addition, the method based on TLD

Table 3 – Deviation (in percentage) between the EBT2 film and TLD measured values of anisotropy function.

Radial distance, r (cm)	Angle, θ (°)						
	30	45	60	90	120	135	150
1.0	0.66	1.82	2.54	0	1.52	2.24	0.86
2.0	3.12	1.90	0.88	0	−1.23	−2.81	−1.60
3.0	3.12	1.69	0.80	0	0.96	0.72	−0.34
4.0	3.82	2.54	1.75	0	0.32	0.96	−0.20
5.0	2.31	1.50	1.73	0	1.53	2.19	3.89
6.0	3.78	1.73	1.94	0	1.26	3.91	3.54
7.0	3.49	2.68	2.09	0	0.39	1.28	2.08
8.0	3.47	2.20	2.08	0	0.97	2.48	−0.40
9.0	0.60	2.08	−0.03	0	−0.14	−2.11	0.75
10.0	0.76	−0.34	−1.26	0	1.61	0.62	0.96

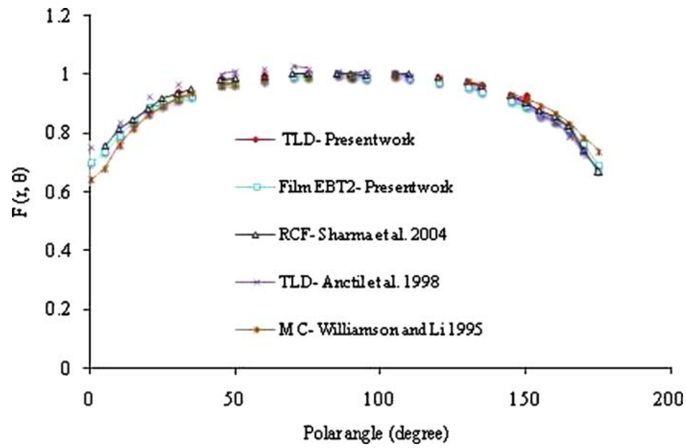

Fig. 3 – A comparison between values of anisotropy function at 5 cm measured with TLD and Gafchromic EBT2 film in the present work and with radiochromic film, TLD and Monte Carlo values reported by other investigators for the same source.

is labour intensive and time consuming. However, as a validated method in brachytherapy dosimetry, thermoluminescent dosimetry has been used as a reference method for comparison with other methods using different detectors. The Gafchromic EBT2 film used in this work provides a high spatial resolution with small detecting volume; as a result, it is especially suitable for measuring doses in high dose gradient regions near the source. The angular variation of the anisotropy function measured from the Gafchromic EBT2 film is expressed in more detail than TLD dosimetry at discrete positions. Although the dose response for this film is nonlinear, it has a low energy dependency within calibration and measuring source energies.

5. Conclusion

This work presents a simple method in which a Gafchromic EBT2 film and TLD detectors were employed in a single experimental set up to evaluate the anisotropy in the dose distribution of the microSelectron ^{192}Ir HDR source. The generated TLD and film data are in agreement with each other and also comparable to both experimental and Monte Carlo calculated results for this source reported in the literature, to within the uncertainty of the measurement. Thus, this work demonstrates that a Gafchromic EBT2 film can be successfully used for experimental evaluation of spatial distribution of dose around the source with optimal accuracy. As compared to TLD, the dosimetry with a Gafchromic EBT2 film was found to be a less expensive, simple to use and high resolution method. The illustrated work can also be used for other sources to produce dual dataset in a single experiment for a faithful comparison. The presented method may also be used with other solid state detectors and for other sources by creating minor changes in phantom design and settings.

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